Two-Fraction Model of Initial Sediment Motion in Gravel-Bed Rivers

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The prediction of sediment transport in gravel-bed rivers is essential to the management of land, water, and ecological resources in mountain regions. Dividing the bed sediment into two populations—sand and gravel—permits realistic and useful predictions of the onset of sediment transport. The critical flow initiating grain motion decreases rapidly with sand content over the transition from a gravel-framework bed to a sand-matrix bed. The two-fraction model provides a simple means of forecasting the movement of excess fine sediment supply. The model also helps to explain the development of the abrupt gravel-sand transition commonly observed in natural rivers.

The mix of grain sizes in a riverbed depends on the rates at which different sizes are supplied to the river and the rates at which the flow transports them. If the water and sediment supply are changed, the river channel will begin to adjust its geometry and bed composition toward a new configuration capable of carrying the altered load (*1*). A pervasive problem in gravel-bed rivers is fine-grained sediment loading from watershed disturbances (for example, fire, land development, road construction, logging, and reservoir operation). Storage of this fine sediment in a riverbed changes its hydraulic properties, reduces habitat for fish and invertebrates, and degrades spawning habitat (*2*). To address the magnitude and duration of these impacts, it is necessary to predict separately the transport rates of the fine and coarse portions of the sediment load, so that changes in bed composition and the residence time of fine-grained sediment can be determined.

The traditional approach has been to calculate the transport rate for a single characteristic grain size, for example, the median (*3*). Because this method does not account for different sizes moving at different rates, it is likely to underpredict the transport rate of sand, which may be much larger than that of gravel (*4*). More recently, transport rates have been estimated separately for many individual fractions (*5, 6*). This approach allows different sizes to move at different rates and can predict changes in grain size, although at the expense of greater computational effort. The fractional approach is sensitive to local detail of the bed size distribution. Transport rate estimates based on the median-size method are tractable but unrepresentative, whereas estimates based on the fraction-by-fraction method are potentially accurate but impractical because the necessary local size information is typically unavailable.

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An alternative is to divide the sediment into only two size fractions, sand (grain size $D_s < 2$ mm) and gravel ($D_g > 2$ mm). Such a two-fraction approach is practical because a two-part bed composition may be measured more readily than the complete size distribution (*7*). This approach also allows sand and gravel to move at different rates.

The transport rates of sand and gravel depend on the proportion f_s of sand in the bed (*8*), not only through its influence on the amount of sand and gravel available for transport (a factor included in present models), but also through the influence of f_s on the inherent transportability of each fraction (*9*). Because the proportions of sand and gravel in the bed sum to 1, the influence of bed composition on transport rate can be represented in the two-fraction model as a simple function of f_s. This interaction between bed composition and transport is missing from previous two-part computations of sand and gravel transport (*10, 11*).

The two-fraction approach is demonstrated here for part of the transport problem: the critical value of the bed shear stress τ_c that produces incipient motion of the sand τ_{cs} and gravel τ_{cg}. This part of the problem is developed first because the governing relations can be almost entirely derived from existing observations and because some results of general importance immediately emerge. A focus on τ_c may not be overly limiting, because it has been shown that transport rates for different grain sizes tend to fall about a common curve when the bed shear stress τ_0 is scaled by the correct critical shear stress τ_{ci} for each size (*5, 6*).

The variation with f_s of τ_{cs} and τ_{cg} is constrained by values in the limit of vanishing amounts of gravel ($f_s \rightarrow 1$) or sand ($f_s \rightarrow 0$). Values of τ_{cs} for clean sand ($f_s = 1$) and τ_{cg} for clean gravel ($f_s = 0$) are known from empirical relations for narrowly sorted sediment, for which the dimensionless critical shear stress τ_c^* is equal to ~0.04 for sizes larger than ~0.5 mm (Table 1) (*12*).

Values of τ_{ci} for the other two limiting cases depend on interactions between the two fractions. As $f_s \rightarrow 0$, the small amounts of sand in the bed will tend to settle between the gravel grains, leaving little or no sand exposed to the flow. Transport of the sand requires entrainment of the gravel, so it may be expected that $\tau_{cs} \approx \tau_{cg}$ and [from the definition of τ_c^* in (*12*)] $\tau_{cs}^* = \tau_{cg}^*(D_g/D_s)$. Because trace amounts of sand should not influence τ_{cg} as $f_s \rightarrow 0$, τ_{cs}^* should approach $0.04(D_g/D_s)$ as $f_s \rightarrow 0$.

As $f_s \rightarrow 1$, the influence of surrounding grains on the motion of a gravel clast becomes small relative to the influence of the weight of the gravel clast and the drag force acting on it. Because τ_{cg}^* represents the ratio of these two forces, a minimum value of τ_{cg}^* can be hypothesized. A minimum $\tau_c^* \approx 0.01$ has been observed for the entrainment of individual instrumented grains as they were progressively elevated relative to the remainder of the bed (*13*). A similar minimum value has also been suggested for the largest grains in a mixture (*14*).

The ratio τ_{cs}/τ_{cg}, a measure of the relative transportability of the sand and gravel fractions, may be calculated from the limiting values of τ_{ci}^* in Table 1. For $f_s = 0$, $\tau_{cs}/\tau_{cg} \approx 1$. For $f_s = 1$, $\tau_{cs}/\tau_{cg} \approx 4(D_s/D_g)$. Because D_g is one or more orders of magnitude larger than D_s in many gravel-bed rivers, the decrease of τ_{cs} with f_s is larger than that of τ_{cg}, suggesting that sand becomes relatively more transportable as f_s increases.

Although both τ_{cs}^* and τ_{cg}^* decrease with f_s, the nature of this variation remains to be determined. At small f_s, a riverbed is made up of an interlocked framework of gravel grains. For $f_s >$ ~0.2, individual framework grains begin to lose contact. At $f_s >$ ~0.4, the gravel framework is replaced by a sand matrix with interbedded gravel clasts (*15*). In matrix-supported beds, abundant sand is exposed on the bed surface at all flows, and sand transport rates should approach those of a purely sand bed. Gravel entrainment is no longer influenced by adjacent gravel clasts and depends primarily on local exposure by sand scour. Thus, much of the variation in τ_{cg}^* and τ_{cs}^* is likely to occur within $0.20 < f_s < 0.4$. A similar transition has been demonstrated in small-scale flume experiments in which a transition between

Table 1. Approximate values of dimensionless critical shear stress at the limits of sand content.

	Clean gravel ($f_s = 0$)	Clean sand ($f_s = 1$)
τ_{cg}^*	0.04	0.01
τ_{cs}^*	$0.04(D_g/D_s)$	0.04
τ_{cs}/τ_{cg}	1	$4(D_s/D_g)$

gravel-dominated and sand-dominated transport occurs over a similar range of sand content in the sediment feed (*16*).

The variation of τ_c^* with f_s may be modified by surface sorting, particularly for a framework-supported bed. For f_s greater than ~0.1, the bed contains sufficient sand that the gravel pores begin to fill, leaving some sand exposed on the bed surface. In such cases, selective sand transport can produce well-sorted sand patches and stripes (*17*). Transport within these patches begins at flows smaller than those required to initiate gravel motion, causing τ_{cs} to decrease relative to τ_{cg} (*18*).

The proposed variation of τ_{cs}^* and τ_{cg}^* with f_s was compared with transport data from four gravel-bed rivers and one laboratory sediment. In three of the field cases—East Fork River (*19*), Oak Creek (*20*), and Goodwin Creek (*11*)—the transport of the entire stream was sampled using either a slot trap extending across the entire river width or a weir through which all of the transport was directed. The grain size distributions in these streams vary widely (Table 2) and f_s varies between 0.15 and 0.59 (*21*). In the fourth field case, Jacoby Creek (*22*), transport was measured using repeated traverses with a hand-held sampler and f_s = 0.22, which is close to the transition from a framework-supported to a matrix-supported bed. The laboratory sediment, BOMC (*23*), has a grain size range that is representative of many gravel-bed rivers and is very similar to the size distribution of Goodwin Creek. These data were supplemented by six laboratory sediments with purely bimodal size distributions (*24*) to expand the range of f_s, especially at large f_s.

Because it is difficult to determine the flow at which all transport ceases for natural sediment beds in turbulent flow, τ_{ci} was replaced by a reference shear stress, τ_{ri}, which is the value of τ_0 that produces a small dimensionless reference transport rate of fraction *i* (*25*). Values of τ_{ri} are ~10% larger than τ_{ci} (*6*). In practice, τ_{ri} can be found from the mean trend of the transport rate of sand and gravel plotted as a function of τ_0. The dimensionless form of τ_{ri} is τ_{ri}^*.

The data conformed well to the proposed variation of τ_{cs}^* and τ_{cg}^* with f_s (Fig. 1). For the gravel (Fig. 1A), τ_{rg}^* decreased from ~0.04 at f_s = 0 to ~0.01 at f_s = 1. For the sand (Fig. 1B), τ_{rs}^* decreased from $\tau_{rs}^* \approx 0.8\tau_{rg}^*(D_g/D_s)$ at small f_s to ~0.04 at large f_s. The values of τ_{rs}^* at $f_s \approx 0.2$ suggest that surface sand patches caused τ_{rs} to be somewhat smaller than τ_{rg}. Values of τ_{rg}^* and τ_{rs}^* decreased rapidly between the observations for Oak and Jacoby creeks (f_s = 0.15 and 0.22) and those for Goodwin Creek and BOMC (f_s = 0.34), suggesting that a shift from gravel-bed to sand-bed values of τ_{ri}^* occurred over the narrow range of f_s associated with the change from a framework-supported to a matrix-supported bed. The decrease with f_s of τ_{rs} is larger than that of τ_{rg} (Fig. 1C). From Table 1, the value of τ_{rs}/τ_{rg} at large f_s will depend on D_g/D_s, so the values in Fig. 1C should not collapse to a single trend.

Values of τ_r^* for the purely bimodal sediments conformed well to the trend for the mixtures with continuous size distributions, except that τ_{rg}^* values were somewhat large in the range $0.4 < f_s < 0.6$. The absence of intermode grains in these sediments may permit segregated gravel to persist at f_s as large as 0.6, thereby increasing gravel resistance to motion and increasing τ_{rg}^*.

The influence of f_s on τ_{ci}^* has implications for cases in which watershed disturbance leads to an increased sediment supply and a sandier riverbed. If f_s increases beyond ~0.2, both τ_{cs} and τ_{cg} may decrease abruptly, causing the magnitude and frequency of transport to increase. Because transport rate is a strong nonlinear function of τ_0/τ_{ci}, the increase in total transport is potentially large. Estimates of potential bed aggradation and of the downstream migration of the added sediment need to account for the influence of f_s on τ_{ci}^* and transport rate.

Riverbeds may also become sandier if sediment transport is interrupted by flow diversion. Many gravel-bed rivers have a large sand throughput, such that the percentage of sand in the total annual load is much larger than that in the bed (*4*). If the diverted flows primarily move sand, f_s will increase at the point of diversion until larger uncontrolled flows can move it downstream. An increase in f_s can increase the transportability of both sand and gravel, potentially to a level at which the entire sediment load can be transported by the undiverted flow.

The influence of f_s on τ_{ri}^* provides a description of the mechanism producing the commonly observed abrupt transition from a gravel bed to a sand bed. Grain size typically decreases as one moves downstream along a gravel-bed river. The rate of fining gradually decreases in the downstream direction until the gravel-sand transition is reached. At this point, the rate of fining can increase sharply, and grain size can decrease by one or more orders of magnitude over distances as short as a few hundred meters (*26, 27*). The gravel-sand transition is often located where the transport capacity of the river decreases relative to the imposed load, as a result of a change in river slope, a backwater, or lateral input of fine-grained sediment. Because the gravel-sand transition can occur over a shorter distance than would be implied by the hy-

Table 2. Grain size parameters. D_s and D_g are the median size of the sand and gravel fractions; D_{90} is the size for which 90% of the entire size distribution is finer.

Site	Sand content f_s	D_s (mm)	D_g (mm)	D_{90} (mm)
Oak Creek	0.15	1.2	26	65
Jacoby Creek	0.22	1.0	24	81
Goodwin Creek	0.34	0.6	16	30
BOMC	0.34	0.5	13	30
East Fork River	0.59	0.6	12	28

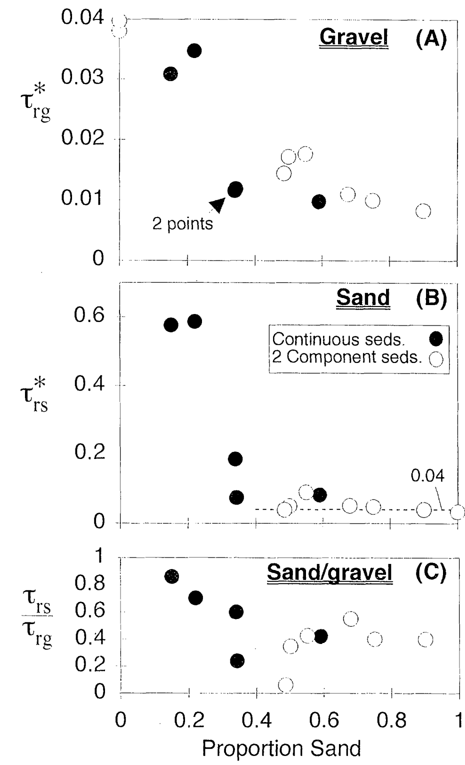

Fig. 1. Dimensionless reference shear stress τ_r^* as a function of f_s for four field cases and one laboratory sediment. (**A**) Gravel fraction; (**B**) sand fraction; (**C**) ratio of sand to gravel reference shear stress. τ_r^* is the value of $\tau*$ producing reference transport rate $W* = 0.002$ (*6, 22, 23*), calculated in all cases using two-fraction plots of sand and gravel transport rate as a function of skin friction τ_0 (Einstein drag partition method with roughness = $2D_{65}$). Both τ_{rg}^* and τ_{rs}^* decrease sharply over a range in f_s that corresponds with the transition from a clast-supported to a matrix-supported bed. The decrease in τ_{rs}^* is proportionately larger. For clean sand and gravel, τ_r^* takes a conventional value of ~0.04. At large f_s, τ_{rg}^* approaches a minimum where grain inertia dominates. At small f_s, sand transport is controlled by gravel entrainment and $\tau_{rs}^* \propto [D_g/D_s]\tau_{rg}^*$. Results of laboratory runs with artificial two-component sediments are shown for comparison, although the absence of intermode grains may permit segregated gravel to persist to $f_s \approx 0.6$, thereby increasing gravel resistance to motion and increasing τ_{rg}^*.

draulic transition, its abruptness suggests a corresponding discontinuity in the sediment transport. One explanation, based on the assumption that transportability varies smoothly with grain size, is that the discontinuity in transport results from a gap in the size distribution of the sediment supply near the sand-gravel boundary (*27*, *28*). Figure 1 suggests an alternative explanation: A small increase in f_s [typically observed immediately upstream of the transition (*27*)] can produce a large increase in the relative transportability of sand and gravel. Where this occurs, τ^*_{ri} should decrease for both sand and gravel, but the decrease in τ^*_{rs} is proportionately larger (Fig. 1C). The resulting enhanced transportability of the sand will accelerate hydraulic sorting at the transition, such that sand, but not gravel, is able to proceed into the lower-energy environment downstream.

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16. In a series of experimental runs in a small flume (*9*), water discharge, water depth, and sediment feed rate were held constant and the percentage of sand S in the sediment feed was varied from run to run. For $S \leq 20$, the observed transport followed the relation for pure gravel. For $S \geq 50$, the transport matched that of a pure sand feed. For $S = 30$ and 40, the observed transport was intermediate between that of sand and gravel. Although a clear transition between sand and gravel behavior was demonstrated, the small flow depths, large Froude numbers, and narrow bimodal size distribution used prevented direct extrapolation to the field case.
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Formation of Carbonates in the Tatahouine Meteorite

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The Tatahouine meteorite, in southern Tunisia, shows terrestrial contamination that developed during 63 years of exposure on Earth's surface. Samples collected on the day of the fall in 1931 contained fractures, with no secondary minerals, whereas samples collected in 1994 contain calcite aggregates (70 to 150 micrometers) and rod-shaped forms (100 to 600 nanometers in length and 70 to 80 nanometers in diameter) on the fractures. Carbon isotope analysis of the carbonates within the Tatahouine meteorite [$\delta^{13}C = -2.0$ per mil Pee Dee belemnite standard (PDB)] and the underlying ground ($\delta^{13}C = -3.2$ per mil PDB) confirm their terrestrial origin.

The fall of the Tatahouine achondrite was observed on 27 June 1931 (*1*). The meteorite broke up along mineral grain boundaries at low altitude or upon impact. Hundreds of fragments were dispersed over a small strewnfield (<1 km^2) on a hill slope composed of Jurassic limestones with a desertic sandy soil. Many fragments were recovered that same day and sent to the Musée National d'Histoire Naturelle in Paris. The weights of the collected samples ranged from nearly 2 kg to 1 g or less. They were composed essentially of large orthopyroxene crystals ($\leq$3 cm) with accessory chromite, iron sulfide, metal, and glass inclusions. The fragments were not highly brecciated by extraterrestrial shock events and display a partly recrystallized igneous texture. Tatahouine was classified as a diogenite (*1*), and this interpretation was confirmed by oxygen isotope systematics (*2*). The strewnfield was revisited in 1994 by Alain Carion, who recovered several small samples (<50 g) by sifting the first few centimeters of soil.

We examined samples and thin sections of Tatahouine collected in both 1931 and 1994. All the samples exhibit preexisting fractures, which were created either during the preterrestrial history of the meteorite or during its impact with Earth's surface. The fractures in the 1931

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